INVESTIGATION ON THE CRACK RESISTANCE AND STRENGTH–DUCTILITY SYNERGY OF TA-12W ALLOY VIA CORRUGATED–FLAT WARM ROLLING

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Tantalum–tungsten (Ta–W) alloys exhibit excellent strength, ductility, corrosion resistance, and high-temperature service stability, making them important high-performance refractory alloys for applications in aerospace and high-temperature electronic devices. However, as typical body-centered cubic refractory alloys, Ta–W alloys are characterized by high deformation resistance, pronounced work hardening, and a high recrystallization temperature. During conventional rolling, these characteristics readily lead to highly elongated banded grains and a strongly concentrated single texture along the rolling direction, accompanied by continuously distributed weakly bonded interfaces along the thickness direction. Consequently, cracks can rapidly propagate along grain boundaries during plastic deformation, resulting in macroscopic delamination fracture. Therefore, a critical challenge in the advanced plastic processing of Ta–W alloys is to reduce their processing difficulty while tailoring the stress state and strain path during rolling, breaking the conventional plane-strain compression-dominated deformation mode, and constructing spatially heterogeneous microstructures to achieve simultaneous improvements in strength, ductility, and delamination-fracture resistance.

To address this challenge, a novel hybrid rolling process, termed electric current pre-treatment + corrugated–flat rolling (E-CFR), was developed for Ta–12W refractory alloy sheets. The evolution of macroscopic stress–strain states, microstructural characteristics, strain localization, and crack propagation under the complex rolling path was systematically investigated. The E-CFR process consists of two rolling passes. In the first pass, corrugated rolling is employed without macroscopic thickness reduction, where periodic variations in the roll profile generate a corrugated sheet morphology and introduce coupled bending, tension–compression, and forward–reverse shear deformation. In the second pass, flat rolling is performed at a 40% reduction to eliminate the macroscopic corrugation while simultaneously reducing the sheet thickness. Before each rolling pass, pulsed-current pre-treatment rapidly heats the material to approximately 300 °C. The Joule heating effect reduces the flow stress of Ta–12W, while the associated electroplastic effect promotes dislocation motion and rearrangement, thereby facilitating stable processing under the complex deformation path. Electric current pre-treatment + flat rolling (E-FR) with the same total reduction of 40% was employed as a reference. Combined with three-dimensional finite element simulations, electron backscatter diffraction (EBSD), transmission electron microscopy (TEM), digital image correlation (DIC), and crystal plasticity finite element (CPFE) simulations, the mechanisms by which E-CFR enhances the strength–ductility synergy and suppresses delamination fracture were elucidated across multiple length scales, from macroscopic deformation to microstructural evolution and fracture behavior.

Three-dimensional finite element simulations demonstrate that conventional flat rolling primarily generates a relatively uniform plane-strain compression state, whereas corrugated rolling substantially alters the internal stress state through the synergistic effects of bending, tension–compression, and shear deformation, producing spatially periodic multiaxial stress states and strain gradients in different regions. The subsequent flat rolling exhibits a pronounced stress–strain inheritance effect from the preceding pass, thereby maintaining and amplifying the pre-established spatially heterogeneous deformation and transforming the dominant deformation mode from uniaxial compression toward coupled shear–compression deformation. Microstructural characterization confirms that the periodic strain gradients transfer the macroscopic heterogeneous deformation to the grain scale, resulting in region-dependent grain morphology, crystallographic orientations, and dislocation structures. The coupled bending–shear deformation promotes the activation of multiple slip systems and grain rotation, suppresses excessive grain elongation along the rolling direction, and substantially increases the diversity of crystallographic orientations and texture components, thereby weakening the strong single texture developed during conventional flat rolling. Meanwhile, heterogeneous deformation promotes dislocation accumulation and rearrangement as well as subgrain formation, establishing microstructural units

with distinct deformation capacities and stored energy levels and providing a microstructural basis for strain accommodation during subsequent plastic deformation.

Compared with conventional flat rolling, E-CFR effectively modifies the spatial distribution of the grain-boundary network. In conventionally rolled material, coincident-site lattice boundaries tend to form continuous band-like arrangements along the rolling direction, providing preferential pathways for crack propagation. In contrast, the periodic strain gradients induced by E-CFR promote grain-boundary reconstruction and discretization of the continuous boundary network, thereby increasing the tortuosity of crack propagation paths. Near the crack tip, a multiscale heterogeneous structure consisting of lath-like deformed grains and fine subgrains is further developed. Dislocation pile-ups, subgrain-boundary barriers, and crystallographic misorientation collectively promote crack deflection and blunting, transforming the continuous intergranular delamination fracture observed in conventional flat rolling into a ductile fracture mode dominated by microvoid nucleation, growth, and coalescence. DIC and CPFE simulations further reveal that the periodic heterogeneous structure generated by E-CFR redistributes plastic strain, extending localized deformation from a single concentrated region toward multiple heterogeneous regions and thereby delaying local plastic instability and necking. The alternating coarse–fine grain structure effectively disperses local stress concentrations and enhances overall deformation compatibility, consistent with the experimentally observed strain delocalization behavior. Therefore, E-CFR not only enhances crack-growth resistance through texture weakening, grain-boundary network reconstruction, and crack-path tortuosity, but also suppresses premature local instability through heterogeneity-induced strain accommodation, enabling a synergistic improvement in strength, ductility, and delamination-fracture resistance. Ultimately, the E-CFR-processed Ta–12W alloy achieves a tensile strength of 969 MPa and an elongation of 34%, demonstrating excellent overall mechanical performance.

Overall, the strengthening and toughening mechanisms of E-CFR can be summarized as follows: First, corrugated rolling introduces periodic strain gradients and multiaxial stress states, while subsequent flat rolling further strengthens the spatially heterogeneous deformation through stress–strain inheritance, ultimately generating a stable heterogeneous microstructure with differentiated grain, texture, dislocation, and grain-boundary characteristics. Second, electric-current pre-treatment reduces the flow stress through Joule heating and promotes dislocation rearrangement and stress relaxation through the electroplastic effect, thereby ensuring stable rolling deformation and thickness reduction. Finally, the resulting multiscale microstructural regulation enables the synergistic effects of crack-growth retardation and plastic-strain delocalization. This work provides a new processing strategy for delamination-resistant forming and strength–ductility synergistic manufacturing of Ta–12W and other high-strength refractory alloy sheets.

KEYWORDS: TA-12W ALLOY – CORRUGATED–FLAT ROLLING – DELAMINATION SUPPRESSION – ELECTRIC CURRENT HEATING – MULTISCALE STRENGTHENING